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THE ORIGIN OF THE INCLUSIONS IN DIKES

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PART I

INTRODUCTION

Several dikes containing numerous inclusions have recently been seen by the writer, and the origin of these inclusions appears to be of sufficient interest to warrant a brief notice of these and other cases found in the literature.[1] The dikes have received various descriptive names, but none of them is sufficiently comprehensive to include all the examples.

Inclusions are not infrequent in all types of both extrusive and intrusive rocks. Those in extrusive rocks have been specially treated by Lacroix. Intrusive rocks are so extensive and of such varying forms that only dikes and a few related intrusions will be considered here. The xenoliths in the large intrusive bodies have formed the basis for the stoping hypothesis, but only part of the inclusions in dikes are of this origin.

Dikes acquire inclusions by shattering blocks off the walls of a fissure during their ascent through it. These fragments may remain near the place from which they came, or they may move up or down. In most cases the fragments rise, whether of greater specific gravity than the molten dike-rock or not, because they are forced upward by the magma. In the cases where the fragments sink, either they are heavier than the magma or they are carried down.

Some dikes have invaded conglomerates, from which they have dissolved the cement and included the bowlders. In other cases the fissures through which the magma came may have been open to the surface, so that stream gravels fell in and were caught in the ascending magma. In rare instances a dike may ascend through a fault breccia and thus acquire its inclusions. These special cases are not separated from the other examples.

To classify dikes according to the direction of movement of the inclusions is difficult, because in almost every case some inclusions rise and some remain near the place of origin. A classification is attempted which will at least serve to emphasize the number of examples in which inclusions sink.

[1] The writer is indebted to Professor R. A. Daly for suggestions concerning this paper.

EXAMPLES

(*A*) *All inclusions near place of origin.*—

Cornwall, England: In the southern part of Cornwall, near Carrick Luz, there is a gabbro boss surrounded by a fringe of gabbro dikes extending outward through the serpentines of the region. All of the dikes contain numerous inclusions of the serpentine. These dikes also illustrate injection foliation.[1]

Da la Bèche reported one of the granite dikes of this region to contain numerous fragments of the slate which it cuts.[2]

Mexico: In the state of Guerrero, Mexico, a granite sill from 12 to 15 feet wide cuts the Juratrias shales, and contains a number of fragments of the slate a foot in diameter. The vertical sill runs parallel to the bedding of the shales, but has evidently broken off the shale inclusions from the walls near the place where they are frozen in the dike. The inclusions are now nearly weathered out of the granite, so that the effect of the heating is indeterminate, but the granite adjoining them shows no immediate contact effect.[3]

Cape Ann, Massachusetts: At Pigeon Cove, Cape Ann, is a labradorite porphyry dike of very coarse grain, 25 feet wide and traceable for 3 miles, everywhere cutting alkaline hornblende granite, but including fragments of diabase and quartzite. The inclusions are about 6 inches in diameter and have a subangular to rounded outline. The numerous diabase dikes now exposed in the region cut the porphyry dikes. The inclusions must have come from quartzites and diabase dikes cutting them, forming the roof of the granite batholith, and must have sunk or been carried down in the dike to their present level. Since that time, which was probably the Carboniferous, the quartzites from the roof of the batholith and the upper part of the batholith itself have been completely removed by erosion. Quartzites appear in small amounts elsewhere in Essex County. The distance through which the inclusions must have

[1] J. S. Flett, "The Geology of the Lizard and Meneage," *Mem. Geol. Surv. Great Britain*, 1912; also, *Proc. Geologists' Association*, XXIV (1913), 127.

[2] *Geological Report on Cornwall* (1839), p. 182.

[3] The writer is indebted to Mr. Y. S. Bonillas for this information.

descended can only be estimated as probably several thousand feet.[1]

(*B*) *Some inclusions have sunk.*—

Montreal, Canada: A number of breccia dikes have been described from the vicinity of Montreal and the Monteregian Hills by Robert Harvie.[2] The dikes will be mentioned in the order in which they are described by Harvie.

Near La Trappe in the Oka Mountains are two inclusion-bearing alnöite dikes, one of which is enlarged to a width of 180 feet, while the other is 25 feet wide and traceable for half a mile. The fragments are of Grenville limestone, Laurentian gneiss, Potsdam sandstone, and Beekmantown sandstone. The last two formations are stratigraphically higher than the exposure which is near the contact of the Grenville and Laurentian. Therefore some of the blocks rose, others sank.

Near Ste. Anne de Bellevue is a dike a foot wide cutting Trenton limestone and containing angular fragments of sandstone, hornstone, and limestone. The sandstone has a quartzitic rim, the hornstone was apparently originally a shale, and the limestone is changed to a crystalline marble.

On Westmount Mountain at Little's quarry is a large breccia camptonite dike about 4 feet wide. In one side of the dike an offshoot from it "has eroded or stoped out and filled a large cavity." The heat of the intrusive has baked the limestone, and a section from the unaltered limestone to the dike shows increasing baking and shattering until the blocks of limestone drop off into the dike-rock, where they form the bulk of the angular inclusions. Harvie says:

> In this process of shattering by which the action of stoping went forward every gradation is visible, from the solid unaltered limestone to the fragments finally frayed off and held in suspension in the breccia. The circulation of the materials of the intrusive has evidently been very vigorous, since fragments of other rocks, granites, etc., are found carried up to the top of the stope within a foot of the unshattered limestone. The magma has not exerted any pro-

[1] The writer is indebted to Professor C. H. Warren, of Boston, for the information concerning the inclusions in this dike.

[2] On the origin and relations of the Paleozoic breccia in the vicinity of Montreal, see *Trans. Roy. Soc. Canada*, 3d ser., III (1909), 249–78.

nounced solvent action on the inclusions, either the basic limestone or the more acid granites; neither has the heat greatly affected the limestone, which one would expect to find in a crystalline state.

There are a number of other breccia dikes in this immediate vicinity, 2 to 7 feet wide, of both a camptonite and a pyroxenite composition. They contain fragments of granite, gneiss, essexite, syenite, Potsdam sandstone, and Trenton limestone, the country rock. All these inclusions have either come from below or from the limestone near by.

It is evident that the inclusions in the cases above mentioned have been derived almost wholly by the dike-magma shattering the walls as it advanced. There must have been an active circulation in the dikes to keep them at a high temperature at the top while they made their way through the limestone and probably through the underlying rocks. This circulation carried up the blocks of the pre-Cambrian and carried down the blocks of the Potsdam and Beekmantown. These dikes appear, therefore, to be cases where the ascent was due, at least partly, to a blowpiping action on the rock overhead.

In the same memoir Harvie describes other dikes and intrusions of various forms, all of which consist of a breccia of similar inclusions in a basic matrix. One of the masses of breccia on St. Helen's Island,[1] near Montreal, cutting Utica shale, contains blocks of fossiliferous Oriskany limestone and Helderberg limestone, indicating the former presence of strata of these ages in the region. It also contains fragments of the Ordovician and older rocks.

The vertical movement of the fragments in these cases is interesting because it has been in both directions in the same dike or mass. This movement does not seem to be dependent on the form of the intrusion nor on the composition of the intruding dike-rock. The thickness of the formations from the top of the Laurentian to the bottom of the Utica is 2,500 feet (Harvie). The Utica is succeeded by Lorraine shales 2,000 feet thick. No higher stratigraphic horizon is exposed in the region, except in the inclusions on St. Helen's Island. Therefore these Devonian fragments must

[1] See also F. D. Adams, *Twelfth Internat. Geol. Cong., Guide Book 3*, p. 55, for a description of these breccias.

have sunk or been carried down over 2,000 feet, and the Laurentian fragments in the same breccia brought up over 2,500 feet. In the La Trappe dike the movement in each direction was probably not as great, but the distance from the Beekmantown down to the contact of the Grenville and Laurentian must have been several thousand feet.

Marblehead, Massachusetts: At Marblehead, Massachusetts, half-way between Peaches Point and Naugus Head, are a number of dikes of pulaskite cutting an igneous complex. These dikes range in width from a few inches to 50 feet. In many cases they appear to follow the course of earlier diabase dikes, all stages being present, from a network of pulaskite veins in a solid diabase dike to a shatter breccia of diabase in pulaskite and finally to a band of schistose streaks of diabase in the center of a broad dike of pulaskite, showing the former position of a diabase dike. In one case there are remnants of two such dikes in a wide pulaskite dike. The diabase fragments are lenticular schistose bands, sometimes several inches in width, in a coarse-grained pulaskite, which grows finer-grained in the small tongues which permeate the diabase inclusions. The dark constituents of the pulaskite appear to have been derived largely from the absorbed diabase. The width of the original dikes was from 1 to 3 feet.

Southern Sweden: At Brevik and at Karlshamn, southern Sweden, diabase dikes filled with rounded inclusions occur. They have been described by Hedström[1] and Eichstädt[2] on whose papers the following description is based. Two of these dikes are known, being mapped on the Eskjö and Karlshamn sheets of the Swedish Geological Survey.

The dike at Karlshamn is 3 miles long and in places several hundred feet wide. The inclusions are all on the west side of the dike and consist wholly of quartzite and quartzitic sandstone. Cataclastic structure is characteristic of all the inclusions, but this texture was caused by metamorphism before the quartzites were

[1] "The Pebble-Diabase of Brevik," *Eleventh Internat. Geol. Cong., Guide Book 18*, 1907, pp. 47–51.

[2] "Om quartsit-diabas-konglomeratet i Småland och Skåne," *Sveriges Geol. Unters.*, Ser. c, No. 74, 1885.

included in the dike. The contact of the pebbles and the diabase in the case of this dike is sometimes sharp and sometimes indistinct. In the pebbles, which have undergone the most marked absorption, it is difficult to distinguish even the center of the pebble. Sometimes ilmenite and fine feldspar crystals have formed in the pebbles with a rim of epidote and chlorite between the pebble and the diabase. The dike cuts Archean gneiss, and none of the younger pre-Cambrian sedimentary series is present in the region.

The "pebble-diabase" dike of Brevik (on the Eksjö sheet) has a strike of about N.–S. and has been traced for about 15 miles. It cuts Almesåkra pre-Cambrian sandstone, quartzite, and conglomerate. The width of the dike varies in different exposures and it often exceeds 300 feet. Inclusions appear only in some of the outcrops, and there they are, as a rule, confined to smaller zones, often 10 to 15 feet in width, which are elongated parallel to the sides of the dike. These zones may be situated either on the sides of the dike, and usually on the eastern side, or near the middle. They vary in width from 4 to 50 feet, changing with the width of the dike. In smaller offshoots from the dike, about 15 feet in width, fragments sometimes occur evenly distributed over the entire width. Elsewhere there is a sharp boundary between the parts free from and full of inclusions.

The inclusions consist largely of quartzite and schist derived from the Almesåkra pre-Cambrian complex, with some granites, leptites, gneisses, and other pre-Cambrian rocks. The size of the fragments varies from a few inches to 30 feet. The shape of the quartzite inclusions is rounded, of the granite, subangular, while the inclosures of schist form thin bands of considerable length, which are surrounded by sheets of diabase. The pebbles are so numerous as almost to touch. They occupy about half the volume of the dike, and at times even more. The inclusions weather out easily.

In the pebble-bearing parts of the diabase the ophitic diabasic structure is not developed, and the presence of the numerous inclusions has caused a segregation of the light and dark minerals into separate spots. There are also grains of quartz and feldspar scattered through the diabase as if derived from the resorption of the edges of some of the inclusions or from the cement of the original

conglomerate from which the pebbles were derived (Hedström's theory). The inclusions of quartzite are generally surrounded by zones in which iron ore, biotite, and chlorite are developed. The contact of the diabase with the quartzite pebbles is, however, usually sharp, while the contact with the sandstone and granite is more or less indistinct, the magma having formed fused contacts and even having penetrated a few of the inclusions. In places a flow structure is developed in the diabase around the fragments.

Eichstädt proposes the theory that the inclusions in both dikes were derived from loose pebbles on the surface of the ground, probably accumulated in valleys, which fell into fissures formed in advance of the diabasic intrusions and were caught in the magma when it ascended in the fissures. In support of this theory he points out that if the blocks of quartzite were originally angular and the edges resorbed where they are now, the silica content of the diabase near the zones of inclusions would be much greater than elsewhere in the dike. This is not the case, although he finds free quartz and micropegmatite present in the diabase of both dikes. He noted the existence of pre-Cambrian conglomerate in the vicinity, but considers that the pebbles were derived from a loosely consolidated conglomerate (as this Almesåkra conglomerate may have been in the pre-Cambrian time when the dikes were formed) and not from a massive conglomerate.

Hedström proposes a somewhat similar theory: that larger and smaller pieces of the Almesåkra conglomerate have been imbedded in the diabase magma. He considers that the conglomerate was at least somewhat consolidated and accounts for part of the matrix by the numerous grains of quartz and feldspar scattered in the diabase. In support of this view he finds inclusions to which portions of the original matrix are still attached. The hard quartzite pebbles in the Almesåkra conglomerate are greatly cracked and show the same cataclastic structure as do those of the inclusions which have often split up into several pieces which have been more or less widely displaced from each other in the magma. The cement of the original conglomerate was gritty, loose, and brittle, and therefore its cohesion was easily destroyed at the intrusion of the diabase. "In the appearance and character of the pebbles, as

also in the proportions of the rock types represented among them, is a perfect agreement between the Almesåkra conglomerate and the pebble-diabase." It should be noted, however, that the Almesåkra series is now present only near Brevik. A former extension of the series for 90 miles south, to Karlshamn, may have existed.

Cripple Creek, Colorado: At Cripple Creek a number of phonolite and rhyolite dikes include or are capped by loose conglomerate and volcanic breccia. These phenomena have been described by G. H. Stone[1] who has confounded the origin of the conglomerate and breccias with that of the dikes. As pointed out by Ransome and Lindgren,[2] the former are stream gravels and volcanic breccias, some of which have been invaded by dikes. It appears probable that the inclusions in the dikes themselves have fallen in from the overlying loosely consolidated beds.

At Grizzly Peak, Colorado, similar granitic breccias have been reported by G. H. Stone[3] and it is probable that here also stream gravels or volcanic breccias have been invaded by dikes.

The manner in which an igneous rock invades a conglomerate is well illustrated in a satellitic stock of the Bayonne batholith in the Selkirk Mountains, British Columbia, as described by R. A. Daly.[4] The granitic magma has eaten its way into the conglomerate,

> dissolving out the cement in large amount, and has thus not only thoroughly impregnated the conglomerate with the granitic material, but has quite separated many of the larger quartzitic pebbles, which, still rounded, are now completely inclosed in granite. The cement was evidently more soluble in the magma than were the quartzite pebbles—a conclusion to be expected in view of the fact that the heterogeneous cement has a lower fusion-point, and in relation to the acid granite, a lower solution-point of temperature, than the more highly siliceous quartzite. The partial absorption of the conglomerate must have taken place when the magma was (because cooled down) sufficiently viscous to allow of the suspension of the blocks and pebbles. At an earlier period, when the cooling was less advanced, the quartzite pebbles

[1] The Granitic breccias of the Cripple Creek Region," *Amer. Jour. Sci.*, Ser. 4, V (1898), 21–32.

[2] *U.S. Geol. Surv., Professional Paper 54.*

[3] *Amer. Jour. Sci.*, Ser. 4, VII (1899), 184–86.

[4] "The Geology of the N. A. Cordillera at the 49th Parallel," *Can. Geol. Surv., Memoir 38* (1914), p. 300.

themselves, like the main quartzitic and schistose formations, could have been dissolved.

Pequawket Mountain, New Hampshire: Pequawket Mountain, the Eastern Kearsarge of New Hampshire, and Moat Mountain, near by, are composed of masses of quartz porphyry, of stock-like form, which contain so many fragments of metamorphic rocks that they have been described as breccias.[1] The Pequawket mass is about 1,200 feet long and 450 feet wide. It lies at the contact of the older Albany granite and slate. The angular inclusions are very numerous, consisting largely of slates, sandstones, and phyllites, derived from the adjacent terranes. The inclusions do not show any alteration at their contact with the porphyry. The porphyry matrix is vitrophyric in the Pequawket mass, granophyric in the Moat mass. As the inclusions do not show as much metamorphism as the surrounding slates, and as the quartz porphyry is not squeezed, Daly concludes that the inclusions have probably come from above the present exposure, where the metamorphism was not so great.

Lages, Brazil: Near Lages, Brazil, an inclusion-bearing dike was found by Woodworth.[2]

The dike is of trap and was evidently the feeder of one or more of the Triassic trap sheets which are exposed in the Lages area. At the outcrop investigated, the width of the dike is 75 feet. Here the inclusions of foreign rocks constitute one-half of the volume of the dike and comprise red and black shale, coarse-grained basalt, fine-grained basic rock, and amygdaloidal basalt. The fragments of sedimentary rock were apparently disrupted from the walls of the fissure which appears to have been a fault-line. Whether they came from above or below the exposure could not be determined. The amygdaloidal basalt fragments must have come from the overlying Triassic flows according to the determination of the geological structure by Woodworth and others. Furthermore, it is certain that the dike was not formed until after other lavas had been extravasated and cooled to yield the inclusions which sank in the fluid dike-magma.

[1] R. A. Daly, *Science*, N.S., III (1896), 752.

[2] J. B. Woodworth, "Geological Expedition to Brazil and Chile, 1908–9," *Bull. Mus. Camp. Zoöl., Harvard*, LXI, No. 1, p. 95.